

Integrated Properties of AGB Stars in Resolved and Unresolved Stellar Populations : Simple Stellar Populations and Star Clusters

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Abstract. The evolution of AGB stars is notoriously complex. The confrontation of AGB population models with observed stellar populations is a useful alternative to the detailed study of individual stars in efforts to converge towards a reliable evolution theory. I review here the impact of studies of star clusters on AGB models and AGB population synthesis, deliberately leaving out any more complex stellar populations. Over the last 10 years, despite much effort, the absolute uncertainties in the predictions of the light emitted by intermediate age populations have not been reduced to a satisfactory level. Observational sample definitions, as well as the combination of the natural variance in AGB properties with small number statistics, are largely responsible for this situation. There is hope that the constraints may soon become strong enough, thanks to large unbiased surveys of star clusters, resolved colour-magnitude diagrams, and new analysis methods that can account for the stochastic nature of AGB populations in clusters.

1. The Upper AGB in Population Synthesis Models

With the advent of near-IR astronomy on one hand and the efforts devoted to the modelling of the chemical evolution of galaxies on the other, it has rapidly become obvious that AGB stars must be included very carefully in all varieties of population synthesis models (Iben & Truran 1978; Renzini & Buzzoni 1986; Charlot & Bruzual 1991). Meetings such as the IAU Symposium held in Montpellier in 1998 or the first edition of the Vienna meetings in 2006 (GALAGB1 hereafter) highlighted the reasons for such an effort and the difficulties to overcome. Today the whole extragalactic community has been warned that stars on the upper AGB (to which we will refer as the TP-AGB hereafter because it is usually associated with thermal pulses) is responsible for more than 50 % of the near-IR light emitted by a stellar population at intermediate ages (a few 100 Myr to one or two Gyr). It may well reach 80 % at a range of ages and metallicities (Maraston 2005; Marigo et al. 2010). AGB stars determine the near-IR mass-to-light ratio of these populations, with critical effects on the estimates of galaxy masses when the universe had an age of order 10^9 years (Maraston et al. 2006).

For this second edition of the Vienna meetings, I was asked to review the current status of population synthesis models for Simple Stellar Populations (SSPs) at ages at which AGB stars are most relevant. This paper therefore excludes any discussion of composite populations. And it focuses on star clusters as approximate SSPs in the real world although there is growing evidence that the fraction of clusters with not-so-simple populations is much larger than one dared to hope a few years ago (Gratton et al. 2004;

Milone et al. 2009). To narrow down the field even more, only models and observations at optical and near-IR wavelengths will be considered, despite the importance of AGB envelopes at the mid-IR wavelengths (Bressan et al. 1998; Vega et al. 2010) and the debated role of post-AGB stars in the ultraviolet (e.g. Brown et al. 2008).

1.1. From stellar evolution models to stellar populations

Most of the population synthesis codes used in the extragalactic community include the AGB through so-called synthetic modelling, i.e. a set of analytic scaling relations that reproduce the main behaviours of detailed interior and evolution models, because computation times still limit the size of the grids that can be produced with the latter. A list of existing synthetic evolution codes has been compiled recently by Marigo et al. (2010). A minimal set of ingredients of synthetic models includes a core mass - luminosity relation, a link between the core growth rate and luminosity, the rate of evolution for the total mass and therefore some prescription for mass loss (which frequently implies estimating a radius or effective temperature), an approximate description of the pulse shapes and the interpulse durations, a description of the impact of 3rd dredge-up and the formation of carbon stars. Both core burning and envelope burning must be accounted for. The most frequently used set of basic relations still is the one by Wagenhuber & Groenewegen (1998), which is based on the original tracks of Wagenhuber & Weiss (1994) and Wagenhuber (1996). Another starting point is Hurley et al. (2000). Modern implementations all include a dependence on metallicity. Some consider abundance ratios, in particular the large effects of the C/O ratio on envelope opacities, which sets the stellar radii and therefore influences mass loss rates and stellar lifetimes. Many of the prescriptions listed above have modern versions with several parameters each, that must be considered essentially free in view of the theoretical uncertainties. This is what is meant in population synthesis jargon when it is said that models need to be calibrated against observations. With more parameters being added to the models, this task is not actually becoming easier as time passes: the number of independent empirical constraints has to grow equally fast. This point is discussed further in Sect. 2.

A few alternatives to synthetic evolution are being used today. One approach is directly based on the “fuel consumption theorem”. This approach bypasses the calculation of the time-dependent location of evolving stars in the HR-diagram, and focuses on the total energy radiated by each (spectral) type of post-main-sequence star for a given main-sequence turn-off (as originally done by Tinsley & Gunn 1976). The number of free model parameters is kept small and the main scaling relations are taken from observations of star cluster samples whenever possible (Maraston 2005). The opposite approach, meant to force agreement with nature and highlight shortcomings of current synthetic models, with no claim to ensure physical consistency, is to add even more free parameters to existing population synthesis models and vary them radically (Conroy & Gunn 2010). Finally, at least one group is attempting to use modern CPU grids to produce enough complete stellar interior and evolution models to avoid the need for analytic prescriptions for interpolation and extrapolation (Puzia et al., in preparation). The resources needed to work with this approach are costly even for today’s standards, and of course the fundamental uncertainties related among others to the choice of a criterion defining convective boundaries, of a set of nuclear reaction rates, and of a mass loss prescription are not removed.

It takes some time for the latest findings derived from specialised stellar evolution calculations to spread out into the realm of stellar population studies. One example

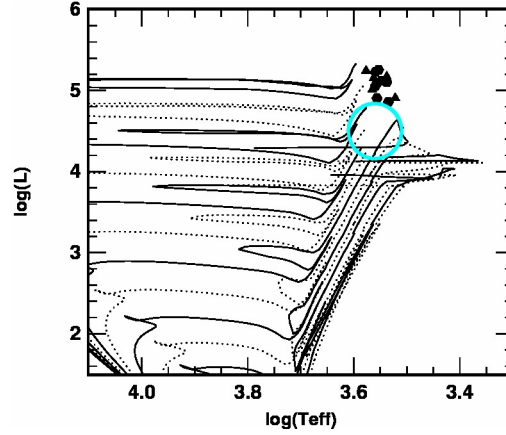


Figure 1. The super-AGB gap. The isochrones shown for $Z=0.008$ and ages between 10 Myr and 4 Gyr are from Marigo et al. (2008); the thermal pulses of super-AGB stars are not included. Symbols represent the LMC/SMC red supergiant sample of Levesque et al. (2007). The light coloured ellipse highlights the typical “zone of avoidance” of empirical samples of either red supergiants or AGB stars.

of such a delay is seen currently in the absence of super-AGB stars in widely used population synthesis codes. Super-AGB stars form the boundary between traditional low or intermediate mass stars that will form carbon-oxygen white dwarfs, and massive stars that will explode as supernovae after burning not only carbon but also its products. They are predicted to manage to burn only carbon before either forming neon-oxygen white dwarfs or exploding as electron capture supernovae (e.g. Ritossa et al. 1996; Poelarends et al. 2008; Siess 2010). They undergo thermal pulses before they die, and become extremely luminous ($\sim 10^5 L_{\odot}$), but in many (all?) current population synthesis codes the stars simply disappear when the available evolutionary tracks end, i.e. before the thermal pulses. A symptom of the disarray is that empirical samples of red supergiants on one hand, bright AGB stars on the other, tend to carefully avoid the region of confusion, and that it therefore remains difficult to find samples of candidate super-AGB stars (Fig. 1).

1.2. From stellar populations to emission properties

The output of evolutionary calculations, combined with a stellar initial mass function (IMF) and the assumption of a single stellar population (all stars have equal age and initial composition), is a distribution of stars across evolutionary stages, which is generally made available as a set of luminosities (or gravities), effective temperatures and surface abundances. Predicting the emission of such a population when TP-AGB stars contribute strongly remains a serious challenge.

TP-AGB stars are cool, and model atmosphere calculations coupled with detailed radiative transfer codes in spherical symmetry have been demonstrated to reproduce observations well for static M-type giants only above about 3500 K. Even in that range of temperature the demonstration of the models’ ability to match high resolution optical and near-IR spectra simultaneously is still absent due to lack of adequate reference observations. Projects such as the ongoing Xshooter spectral library could help here (PI S. Trager, see Chen et al. in this volume). At cooler temperatures, the models seize

the main trends but do not match optical and near-IR data with the level of consistency required for common stellar population studies. A main cause for trouble is that real cool giant and supergiant stars are all variable in one way or another, with irregular variations due for instance to surface inhomogeneities related to surface convection, or for luminous AGB stars long period variations associated with pulsation. Models for the spectra of Mira-type pulsators on the TP-AGB are in their youth (Tej et al. 2003; Lebzelter et al. 2010), and the continuing efforts of the few teams devoting their time to these calculations and their physical ingredients are recognized by the population synthesis community as extremely important. As summarized by S. Höfner (this volume), current models remain highly simplified, and rather than on the output spectra they still focus on evolutionary aspects, in particular the formation of dust grains capable of driving the wind that leads to the ejection of the envelope; nevertheless, with new ideas on the nature of the dust particles that might play this role, late M-type TP-AGB stars receive fresh attention. Non-linear pulsation models, such as constructed by Olivier & Wood (2005) for instance, are not as yet combined with detailed atmosphere and radiative transfer models.

The principles of dust formation in TP-AGB stars with carbon-rich atmospheres had been set before GALAGB1. Spectral models for carbon stars exist and are continuously being upgraded (Nowotny, this volume). The grid of static models of Aringer et al. (2009) only contains carbon stars with relatively blue optical to near-IR colours. New calculations with (piston-driven) pulsation models, that produce circumstellar dust, reproduce the range of carbon star colours observed in nature (Eriksson et al., this volume).

The alternative to theory is to work with empirical spectra of AGB stars. The largest collection of empirical spectra directly useful for population synthesis purposes was produced by Lançon & Wood (2000) and Lançon & Mouhcine (2002). It is included in the spectral synthesis models of Mouhcine & Lançon (2002); Maraston (2005); Raimondo (2009); Percival et al. (2009). The Xshooter spectral library already contains observations of about a hundred such stars.

It must be kept in mind that empirical spectra of long period variables (LPVs) don't carry a label indicating the fundamental parameters of the observed stars. Without a final theory for the time-dependent emission of LPVs, the assignment of an effective temperature or a mass can not be very reliable. Let alone the assignment of the effective temperature of the "static parent" of the star. But just that is what is needed to attach an empirical spectrum (time-averaged over the pulsation cycle) to a particular point of a theoretical stellar evolution track or isochrone. Tracks have enough trouble dealing with thermal pulses and never consider the *systematic* effect pulsation is expected to have on the average effective temperature of a star (e.g. Hofmann et al. 1998). Illustrations of the issues are provided in Lançon & Mouhcine (2002). The uncertainties associated with the connection between a point on a theoretical track and a representative spectrum on the TP-AGB are *larger* than those associated with the value of the theoretical (non-pulsating) effective temperature.

With thousands of observations of LPVs across optical and near-IR wavelengths, rather than hundreds, it should become possible to define better correlations between spectral properties and pulsation properties (pulsation mode, period, amplitude) than available today. Such a project would take a long time, but it seems that obtaining the equivalent theoretical sequences of intermediate resolution spectra will take even longer. Pulsation models can predict periods along evolutionary tracks, maybe also

amplitudes, which in the end could help selecting the right spectrum for any given evolutionary stage. This idyllic path into the future darkens a bit if one remembers that stability against pulsation and pulsation properties are sensitive to the very outer stellar layers and to poorly understood physics such as convection (see Wood, this volume).

At present, carbon stars seem somewhat easier to deal with than oxygen-rich LPVs. Indeed, the variance between the spectral features observed in carbon star samples is much smaller than for their oxygen-rich counterparts. The question of S-stars has until now been avoided in the population synthesis community by arguing that this phase of evolution is short compared to others, which is the case if an S-star is defined as having a C/O surface abundance ratio very close to 1. At optical wavelengths, S-stars differ from M-stars as soon as $C/O \approx 0.5$ (van Eck, this volume). More relevant to the emission of a stellar population as a whole is what happens around $1\ \mu\text{m}$ or beyond. It is probably worth reconsidering possible effects.

2. Calibrating SSP models against observations of intermediate age clusters

The calibration of AGB population synthesis models against observations is the determination of a set of model assumptions and parameters that optimizes the correspondence with available data. Typical sets of data that have been used (often jointly) in this process include the luminosity functions of AGB stars and of carbon stars in the Magellanic Clouds, the ratio of M stars to C stars in various Local Group galaxies, the abundance patterns seen in planetary nebulae. The colours of high redshift galaxies, which are not contaminated by any stars older than a few Gyr, also provide direct constraints on the energy released by stars on the AGB. Finally, resolved HR diagrams of nearby galaxy field stars will increasingly contribute to providing constraints on AGB models.

Star clusters play a fundamental role in the calibration stellar population models. The ages at which AGB stars contribute to the light budget are spread over a range wide enough that one can expect useful constraints even with internal age spreads of order $10^8\ \text{yr}$ (Milone et al. 2009). The effects of internal abundance spreads, rotation and binarity on the TP-AGB model calibration process remain to be evaluated.

The cluster systems of the two Magellanic Clouds are traditional calibration samples (Ferraro et al. 1995; Maraston 1998; Mouhcine & Lançon 2002). In the Clouds, Bica et al. (2008) identified thousands of clusters and associations, and hundreds of these are thought to have intermediate ages (Chiosi et al. 2006; Glatt et al. 2010; Chandar et al. 2010a). However, the samples used for the calibration of currently used population synthesis tools include only a few tens of these objects. In addition, the selection criteria defining the samples are usually described too superficially to allow a proper study of biases.

A major, very serious caveat of the Magellanic Cloud clusters is that only very few high mass clusters are found among them. Mass distributions of star clusters in galaxies tend to fall steeply with increasing mass, therefore it takes very large ensembles of clusters to find many massive ones. In the Milky Way, the number of massive intermediate age open clusters is even lower (Popescu & Hanson 2010). Comparisons with other intermediate age cluster samples remain relatively rare (e.g. Vázquez & Leitherer 2005; Mouhcine et al. 2002, among others).

What clusters can be considered “massive enough” for the particular task of calibrating AGB models? Clusters are mostly used to test the age and metallicity depen-

dence of model colours. $V - K$ is directly sensitive to the total contribution of cool stars (they contribute little in V and very strongly in K), while near-IR colours such as $J - K$ help constraining the nature of the cool stars (O-rich or C-rich, effective temperature). A single cluster is massive enough if its colours can be considered representative of a population of a given age and metallicity. TP-AGB stars are both luminous and intrinsically rare. With standard stellar initial mass functions, there will be 1 TP-AGB star for some 10^4 stars in total, and that one will produce 70 % of the K band light. Poisson statistics tells us that it will take about 100 TP-AGB stars, i.e. (model-dependent) total masses around $5 \times 10^5 M_{\odot}$, to restrict natural dispersion in TP-AGB numbers (between clusters of the same age, metallicity and total mass) to less than 10 % of the average (Lançon & Mouhcine 2000). This is also the condition for one cluster to display a $V - K$ colour within 10 % of the mean. At lower masses, only a handful of TP-AGB stars produce most of the clusters' near-IR light, and both the exact number and the current spectral type of these will have strong direct effects on the clusters' spectra and colours. Awareness of the so-called “stochastic fluctuation problem” and the non-gaussian colour distributions that result from it, dates back to the 1970s (Barbaro & Bertelli 1977; Girardi & Bica 1993; Santos & Frogel 1997).

A proposed solution to this problem has been to sum individual observed clusters, thus constructing “superclusters” with total masses of order $10^6 M_{\odot}$. González-Lópezlira et al. (2005) and Pessev et al. (2008) have invested considerable efforts in producing supercluster data that include near-IR fluxes. The trend is that these supercluster don't display colours nearly as red as those that were thought representative based on individual clusters: $V - K$ peaks around 2.5 for Magellanic Cloud superclusters, instead of 3.5 in the sample of individual clusters most frequently used previously (Persson et al. 1983). Difficulties in matching optical and near-IR apertures for the integrated photometry of star clusters on a crowded background explain parts of the discrepancy (Pessev et al. 2008). Several of the current population synthesis models do reach $V - K = 3.4$ at Magellanic Cloud metallicities (Maraston 2005; Marigo et al. 2008). Also, the reddest colour occurs shortly after 10^8 yr of evolution in those models, while the ages assigned to the reddest empirical superclusters (based on optical colours, spectra or resolved colour-magnitude diagrams) are of about 1 Gyr. Thus, it seems that the calibration process of the TP-AGB population synthesis models needs to be reconsidered (for further discussion, see González-Lópezlira et al. 2010; Pessev et al. 2008; Conroy & Gunn 2010). As we will now argue, work on the cluster data will be as important as work on the models.

The “supercluster” procedure is a valid method of reducing errors on the estimate of the mean colours *as long as no biases are introduced* when selecting and age-dating the cluster samples used as input. In current samples, selection biases have not been described well enough. Mostly, the choice has been driven by technical considerations : compactness, a reasonably uniform and not too crowded stellar background, no obvious dust lanes across the cluster image, etc. Characterizing selection biases and attempting to construct unbiased samples will take considerably more work, as it requires extensive artificial cluster experiments, or at least a study of the effects of magnitude limits on clusters with finite numbers of stars. Large collections of discrete synthetic clusters are becoming available for such work (Deveikis et al. 2008; Cerviño & Valls-Gabaud 2009; Popescu & Hanson 2010; Fouesneau & Lançon 2010).

Discrete synthetic clusters help illustrating why the risk of biases is strong. Figure 2 shows the predicted loci of clusters in colour-colour space at $Z=0.008$, the metal-

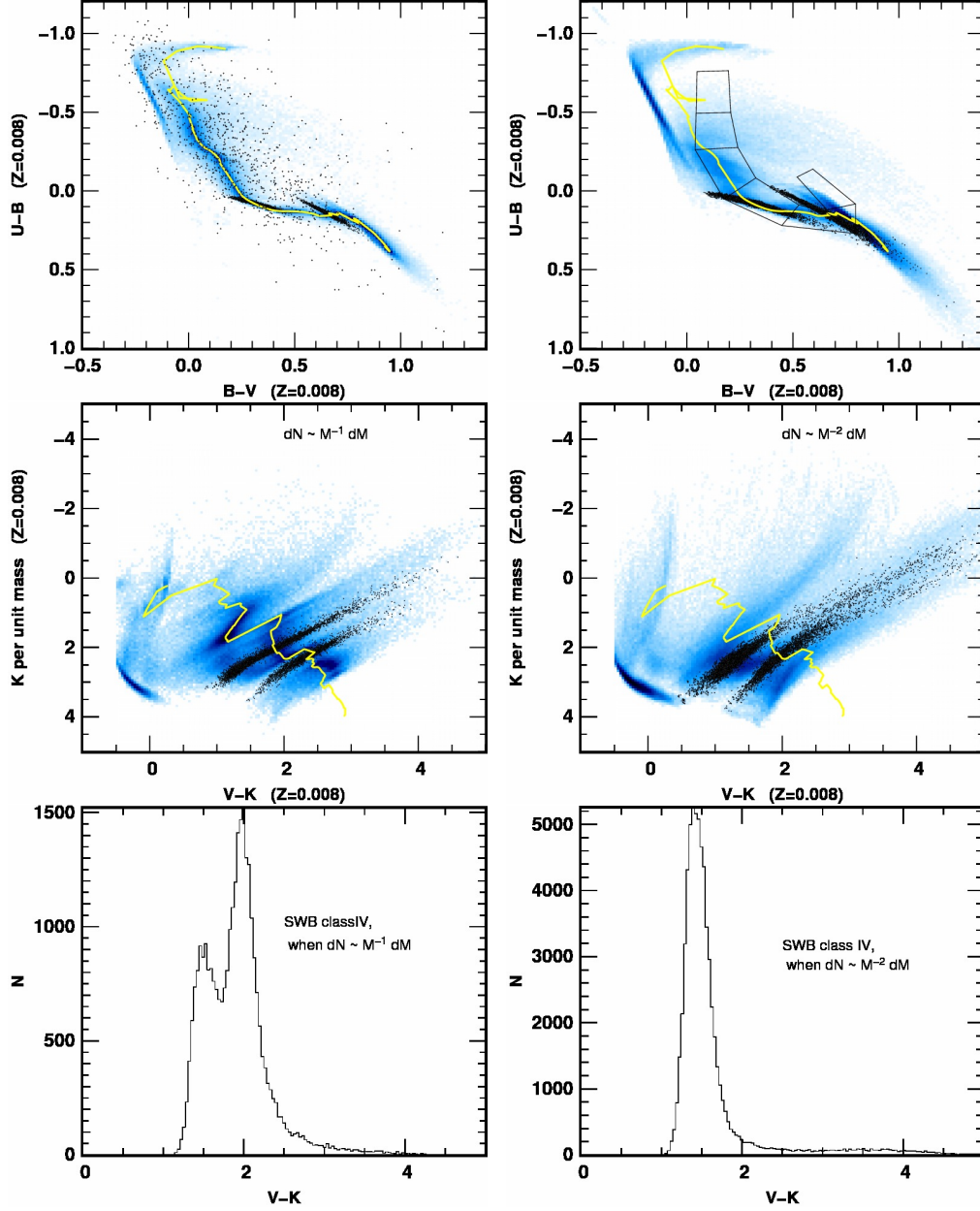


Figure 2. *Top*: The integrated colours of clusters are relatively well-behaved at the optical wavelengths frequently used for approximate age-dating. Displayed are the loci of models at $Z=0.008$ for two cluster mass distributions (M^{-1} on the left, M^{-2} on the right). Overlaid in the left panel are LMC clusters of Hunter et al. (2003). The boxes in the right panel delineate the SWB-classes I to VII of Frenk & Fall (1982), corrected approximately to zero reddening). Clusters with ages of 500 Myr and 1.5 Gyr are highlighted in black. Solid line: locus of very massive stars. *Middle*: Near-IR fluxes are strongly affected by rare luminous red stars such as TP-AGB stars. Clusters with given UBV properties will display a wide range of $V-K$ colours and K -band mass-to-light ratios. *Bottom*: $V-K$ colour distribution predicted for collections of star clusters of SWB class IV (i.e. intermediate age clusters).

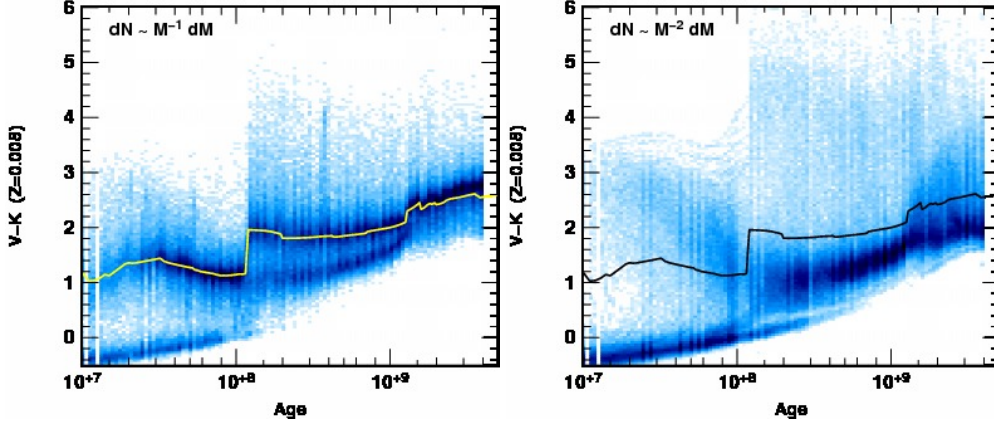


Figure 3. The run of $V - K$ versus age for discrete star clusters at $Z=0.008$, with two cluster mass distributions (solid line : most massive clusters). Synthetic clusters produced by M. Fouesneau, as described in Fouesneau & Lançon (2010).

licity of intermediate age LMC-clusters. When most of the clusters are small, only very few are expected to lie along the line that marks average properties: meeting the average with a small cluster would require a non-integer number of red stars. In view of the natural dispersion in the colours at a given age, the UVB plane allows us to group observed intermediate age clusters into no more than four or five bins of intermediate ages. Note that extinction moves clusters along the age sequence and blurs the picture (see also Girardi et al. 1995), and that uncertain stellar model ingredients such as overshooting affect main sequence lifetimes and the age-colour relation of isochrones.

In the near-IR, colour distributions are highly asymmetric. The models used in Figure 2 have the assumptions described in Fouesneau & Lançon (2010). They include a very simple TP-AGB based on Groenewegen & de Jong (1993)¹. With these models, the populous clusters have $V - K$ between 1.7 and 2.4. However, lower mass cluster $V - K$ colours are spread between 1.3 and 4.5, depending on the exact number and nature of TP-AGB stars they happen to contain. Many have no TP-AGB star and are very blue. It is easy to imagine observational biases, in favour of clusters with either more or fewer TP-AGB stars than the average. Contamination by field stars adds uncertainties to the colours.

In the future, it will make sense to combine the use of “superclusters” with the analysis of complete star cluster populations of galaxies. The comparison of Figure 3 with those of other authors, for instance with Fig. 8 of Marigo et al. (2008) or Fig. 2 of Popescu & Hanson (2010), shows that the expected distributions of cluster colours in age-colour planes depend on the adopted stellar tracks: large observed cluster samples can serve TP-AGB calibration purposes that way. The difficulty of assigning individual clusters an age can be avoided by plotting $V - K$ against optical colours (see Fouesneau & Lançon, 2010, for age assignments in the stochastic context). For the comparison between theoretical and observational distributions to be meaningful, selection effects and uncertainties must be included in the model predictions, in a way similar to what is common practice when resolved colour-magnitude diagrams of stars in Local Group

¹ As in Pégase.2, ftp://ftp.iap.fr/pub/from_users/pegase/PEGASE.2/

galaxies are compared to synthetic diagrams. The comparisons will yield constraints not only on the TP-AGB evolutionary tracks, but also on the age and mass distributions of the clusters observed. With samples of thousands of clusters of all masses, I expect that first order questions such as the average contribution of TP-AGB stars as a function of average optical colours can be answered despite potential degeneracies with parameters of the cluster formation histories.

3. The future : colour-magnitude diagrams, large samples, methods that account for stochastic fluctuations

The recent past has seen the advent of many large surveys, and this trend will continue. The nearest galaxies in particular will be studied extensively both from the ground and from space.

Resolved colour-magnitude diagrams are expected to reduce errors in the ages assigned to individual clusters in the nearest galaxies. Ground-based optical colour-magnitude diagrams for about 1500 clusters in the Magellanic Clouds have been analysed by Glatt et al. (2010). Using overlap between their sample and others, they showed that ages based on colour-magnitude diagrams are more robust than those based on integrated colours (that do not as yet account for the discrete nature of the stellar populations of a cluster): the dispersion between authors is below 0.2 in $\log(\text{age})$ in the first case, of 0.3 in the second. However, the overlap between samples is typically of 50-100 objects, which tend to be the most luminous, least contaminated ones. For the majority of the clusters, the isochrone fitting techniques rely to a large extent on a very small number of evolved stars, whose membership is uncertain. Such observations already provide a means of testing age-dating techniques based on the integrated colours of discrete synthetic clusters. The near-IR Magellanic Cloud survey VISTA-VMC (PI. M.-R. Cioni, see Kerber et al. 2009) in particular will help. But the problems of crowding and contamination will be difficult to solve other than statistically.

The ACS Nearby Galaxy Survey and its near-IR follow-up with HST/WFC3 (Cycle 17 proposal, PI J. Dalcanton) will be a mine of constraints on AGB evolution at various metallicities. WFC3 data will also allow the definition of star cluster samples, that will complement field star data in constraining the AGB. WFC3 has already provided new cluster samples for the 4.5 Mpc distant spiral M 83 (Chandar et al. 2010b). The analysis of the optical colours of these clusters with discrete models is started (Fouesneau et al., in preparation). The natural next step will be to use the optical vs. near-IR colour-colour distributions of the clusters to test AGB models.

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